

STRUCTURAL BEHAVIOUR OF UHPFRC CELLULAR BEAMS

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Abstract

Beams with circular or polygonal openings have been used for decades in steel construction. Lately, these beams, also called cellular beams, are increasingly required to allow the passage of technical pipes (heating, cooling, electrical, etc.) and thus to limit the floor thickness. In concrete construction, conducting web openings in the structural elements requires complicated passive reinforcement arrangements which are often difficult to implement. In order to compete with cellular steel beams with spans going from 12 to 30 m, the high mechanical properties of UHPFRC may be the solution to replace, partially or totally, the shear and cracking reinforcement. This paper presents the first results of an experimental study on five prestressed UHPFRC beams with circular openings tested at the University of Applied Sciences, Fribourg.

Résumé

Dans la construction en acier, des poutres à ouvertures circulaires ou polygonales sont utilisées depuis des décennies. Ces poutres à ouvertures circulaires, nommées également poutres ajourées ou poutres alvéolées, sont de plus en plus demandées afin de permettre le passage de conduites techniques (chauffage, climatisation, électriques, etc.) et ainsi limiter l'épaisseur totale des planchers. Dans la construction en béton, la réalisation d'ouvertures dans les âmes des poutres nécessite des dispositions d'armatures difficiles à mettre en place. Afin de pouvoir concurrencer les poutres métalliques alvéolées pour des portées entre 12 et 30 m, les propriétés mécaniques élevées des BFUP permettraient de remplacer, partiellement ou totalement, l'armature de cisaillement et de fissuration. Cet article présente les premiers résultats d'une étude expérimentale sur cinq poutres précontraintes en BFUP avec des ouvertures circulaires, réalisé à l'Ecole d'ingénieurs et d'architectes de Fribourg.

1. INTRODUCTION

As part of a major research program on Fibre Reinforced Concrete, the University of Applied Sciences, Fribourg carried out a set of theoretical and experimental studies on prestressed beams with circular openings, also called cellular beams. These structural elements, comprising regularly-spaced web openings, are mainly used because of their high resistance-weight ratio, the possibility to integrate service pipes within their height, and

aesthetics (Fig. 1). Such profiles usually exhibit complex behaviour since they can experience different failure modes. In steel construction, such girders have been known for decades and have been manufactured through a specific industrial process. In concrete construction, however, the implementation of the openings requires complex passive reinforcement, which is difficult to implement. In order to compete with long span steel beams (12 to 30 m), it is interesting to replace the shear and cracking reinforcement partially or entirely with High or Ultra-High Performance Fibre Reinforced Concrete (HPFRC–UHPFRC) [1-3].

Therefore two experimental studies on prestressed beams with circular openings have been carried out at the University of Applied Sciences, Fribourg. The first study includes five full scale UHPFRC beams whereas the second study includes seven HPFRC beams. The main aims of these studies are to analyse the behaviour of prestressed beams in HPFRC and UHPFRC with circular openings at the serviceability limit state (SLS) and the ultimate limit state (ULS); to determine the influence of the diameter of the openings, the fibre dosage, and the prestressing force; and to propose recommendations and rules for the design of prestressed beams with circular openings.

This paper focuses on the first experimental study of five UHPFRC beams.



Figure 1: Cellular beams and corresponding passive reinforcement

2. MATERIAL PROPERTIES

The test specimens were made in UHPFRC type BSI[®] (Béton Spécial Industriel). The BSI is developed by Eiffage and belongs to the family of UHPFRC as defined in the interim recommendations of the French Civil Engineering Association (AFGC) [4]. The UHPFRC used in this study was produced without heat treatment. It exhibited a compressive strength at 28 days f_{cm28} of 175 MPa and a Young's modulus at 28 days E_{cm28} of 56.4 GPa. The post-cracking response was defined by bending tests on notched prisms and thin plates. The notched prisms were sawed on a large plate of 1 m² representing a part of the beam web. The quality control was performed at each casting day on six 40 x 40 x 160 mm unnotched prisms tested in three points bending tests according to EN 197-1 [5]. The mechanical properties of prestressed and passive reinforcement steel were identified with tensile tests.

The thin plates showed a hardening behaviour in bending, with an equivalent bending stress around 20 MPa as shown in Figure 2. The tensile constitutive laws were identified according to AFGC inverse analysis for thick and thin elements [4].

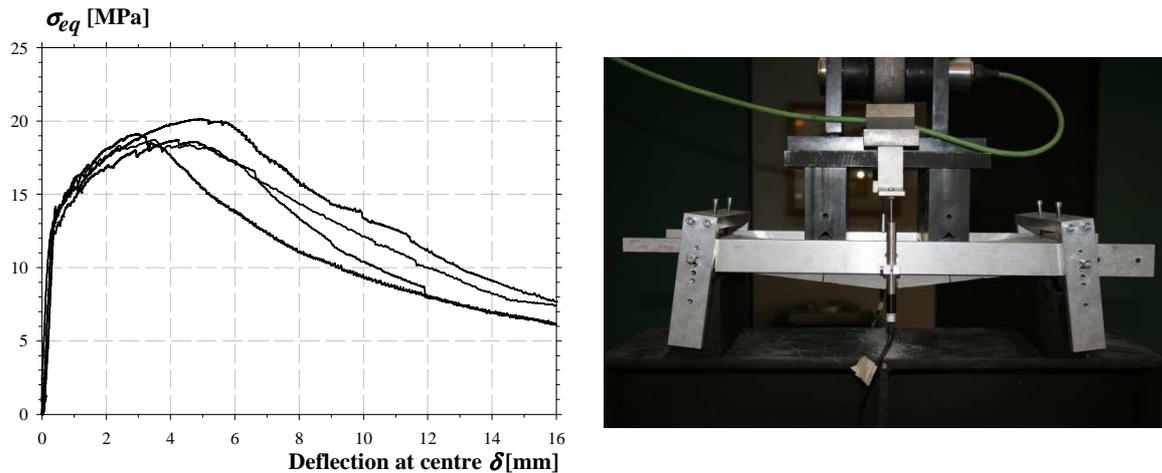


Figure 2: Equivalent bending stress vs. deflection curves at the centre of the UHPFRC plates and corresponding test set-up

3. DESCRIPTION OF EXPERIMENTAL STUDY

The experimental study was conducted on five full scale UHPFRC beams, PU-1 to PU-5, of 9.0 m length (Fig. 3). The cross section was trapezoidal with a height of 1000 mm and a width of 80 mm at the bottom and 100 mm at the top (Fig. 4). Beams PU-2 to PU-5 contain seven circular openings, evenly one meter-spaced. The pre-tensioning was composed of 4 low-relaxation strands (seven wires) with a cross-sectional area A_p of 150 mm² each. The initial prestressing force P_0 introduced in each strand (without losses) was 170 kN for the PU-3 beam and 125 kN for all other beams. Three strands were placed at the bottom of the cross section and one was placed at the top in order to avoid cracking. At the extremities, the beams had six stirrups for the introduction of the pre-tensioning forces. The varying parameters were the diameter of the openings and the prestressing force (Table 1).

The specimens were cast in the precast concrete plant of MFP SA at Cheyres in Switzerland. All beams were cast in a similar manner. A concrete bucket poured the UHPFRC into the framework in several passes, moving from one extremity to the other. The casting process did not pose any problems; due to the UHPFRC's ease of flow no vibration was needed (Fig. 5). The beams were prestressed and removed from the framework after two days.

The tests were performed at the Structural Laboratory of the University of Applied Sciences, Fribourg. The beams were tested on a clear span of 8.00 m. The load was applied at two points, which were symmetrically located at a distance of 2500 mm from the supports, and introduced through steel plates. With this load configuration, the geometrical ratio between the shear span and the effective depth was 2.78. The loading system was composed of steel crossbeams that were connected to four hydraulic actuators of 500 kN by prestressing tie-rods. The actuators were connected to steel crossbeams which were anchored to the strong floor (Figures 6 and 7).

A servo-electronic system controlled displacement during the tests. The displacement rate was 0.02 mm/s representing a quasi-static loading. The load was applied in increments of 50 kN until shear or flexural failure set in. For each step, the cracking pattern and the crack openings were plotted. The recorded data included applied forces, deflections, as well as transversal, vertical, and bottom face displacements.

Table 1: Specifications of the tested beams

Specimen	f_c^* / E_c^* [MPa]	Openings ϕ [mm]	Prestressing force P_0 [kN]
PU-1	181 / 57000	without	4 x 125
PU-2	168 / 57000	400	4 x 125
PU-3	176 / 59000	500	4 x 125
PU-4	178 / 58000	500	4 x 170
PU-5	170 / 51000	600	4 x 125

* Mechanical properties determined at 28 days

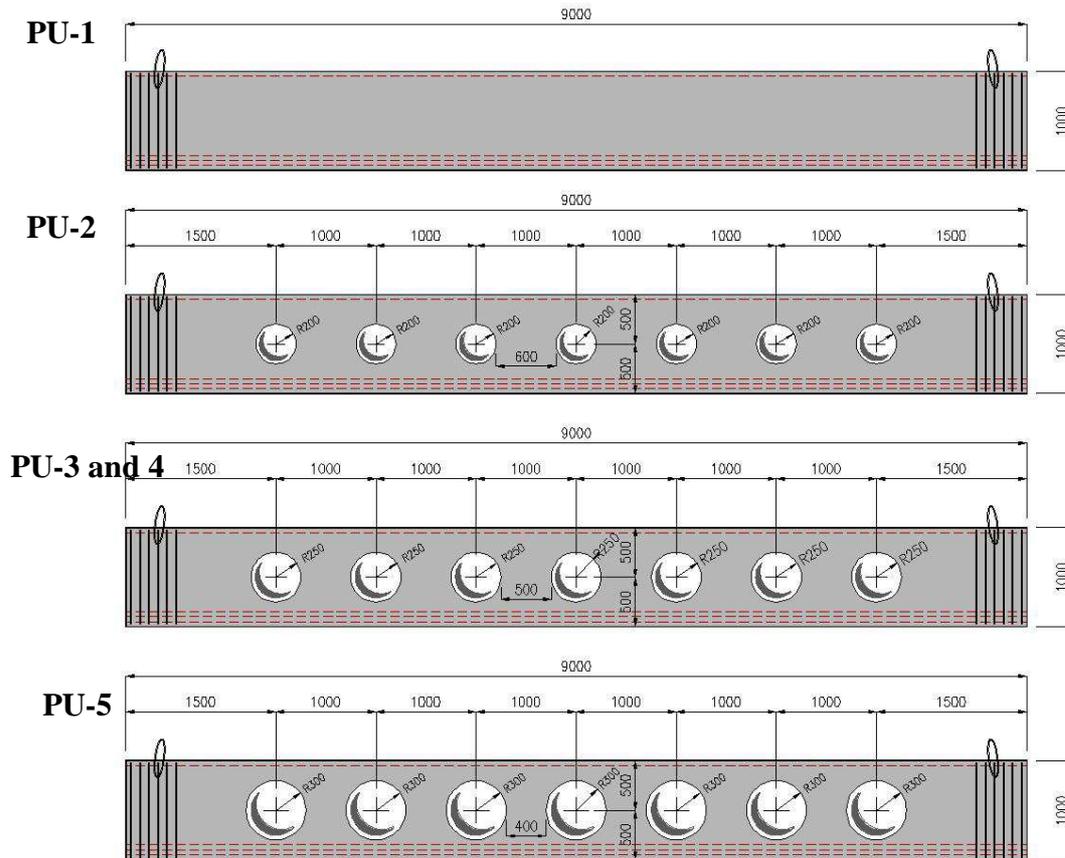


Figure 3: Geometry and reinforcement of the beams

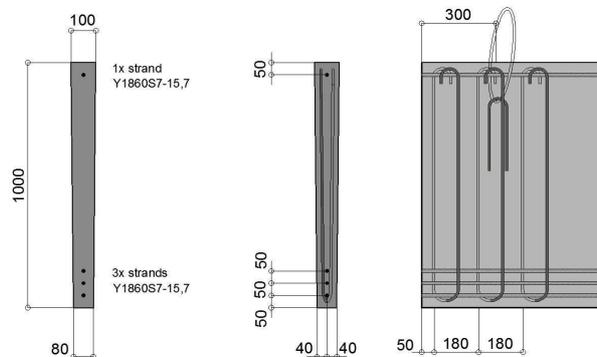


Figure 4: Cross-section and detail of reinforcement



Figure 5: Casting process at the concrete precast plant

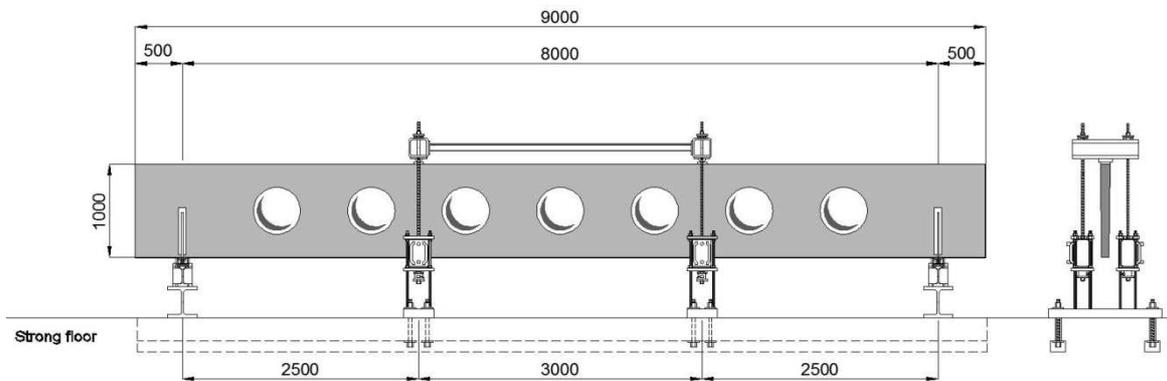


Figure 6: Schematic drawing of test set-up of the cellular beam [mm]



Figure 7: Views of the cellular beam test set-up

4. TEST RESULTS

The test results of the UHPFRC cellular beams PU-1 to PU-5 are shown in Table 2 and the curves load – deflection are presented in Figure 8. Figure 9 illustrates the failure bending mechanism (concrete crushing) for PU-1 and PU-2 without the formation of critical shear cracks. This was similar for both beams, with the small difference that the circular openings

influenced the beam's behaviour as well as the location of collapse. These beams showed micro-cracking and several macro-cracks with approximately 500 mm spaces in between and less than 0.2 mm crack openings.

Specimens PU-3 and PU-4 exhibited a different behaviour and shear failure mode, influenced by the presence of circular openings. Generally, the stiffness and shear strength decreased with an increasing diameter of the openings. The beam PU-5 with larger openings (diameter = 600 mm) acts like a Vierendeel truss. The shear mechanism of specimens PU-3 to PU-5 (Figures 10) was composed of two large shear cracks separating the brace chord between the loading point and the support. The failure was relatively brittle. The influence of the prestressing intensity is revealed in beams PU-3 and PU-4. Specimen PU-4, with a higher prestressing force, showed a higher cracking load and stiffness at cracking state in comparison to specimen PU-3. The shear strength of specimen PU-4 was only 2.4 % higher and the deflection at failure was 24 % smaller.

The shear deformations, corresponding to the sum of LVDT's placed on the shear span at 45° are displayed in Figure 11. Generally, the shear deformations at the same load level increased with the size of the opening. Beams PU-3 to PU-5 exhibited large deformations prior to failure and the deflection shape was clearly discontinuous at the point load.

Table 2: Specifications of the tested slabs

Specimen	Openings ϕ [mm]	Prestressing force P_0 [kN]	Ultimate load F_u [kN]	Deflection at F_u δ_u [mm]
PU-1	without	4 x 125	586.6	62.3
PU-2	400	4 x 125	625.3	78.8
PU-3	500	4 x 125	518.5	59.0
PU-4	500	4 x 170	530.7	45.0
PU-5	600	4 x 125	418.3	44.7

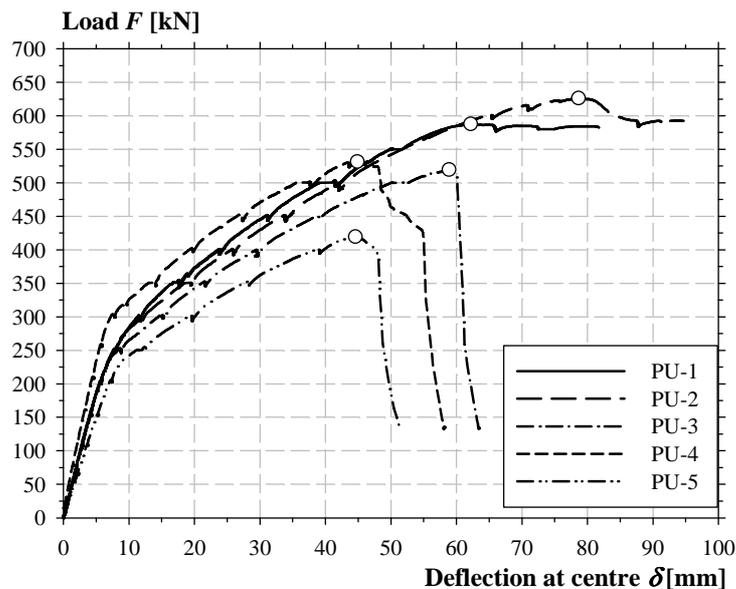


Figure 8: Load vs. deflection curves at centre of the UHPFRC beams



Figure 9: Failure mechanisms of elements PU-1 and PU-2



Figure 10: Failure mechanisms of elements PU-3 and PU-5

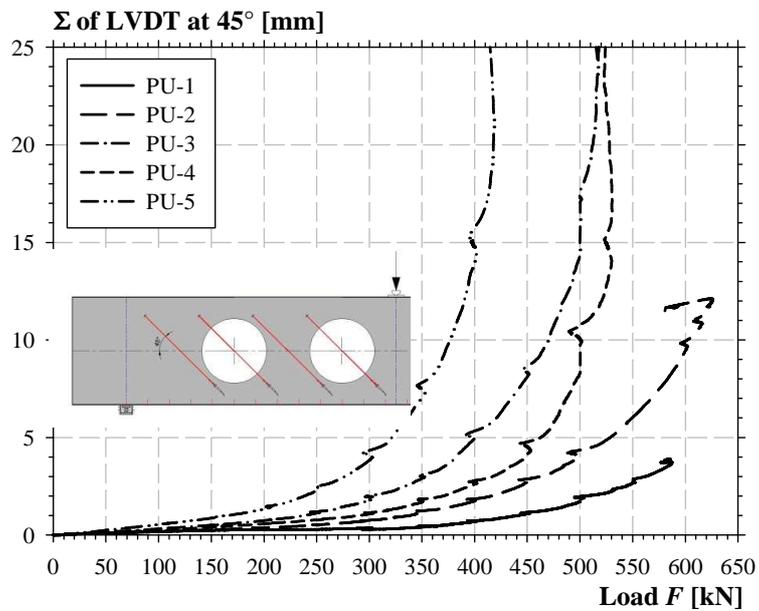


Figure 11: Sum of displacement of LVDT's at 45° vs. load curves of the UHPFRC beams

5. CONCLUSIONS

This paper reports the research program on UHPFRC prestressed beams with circular openings conducted at the University of Applied Sciences, Fribourg. The principal aim of this project was to analyse the behaviour at the serviceability limit state SLS and the ultimate limit state ULS and to propose design models, particularly for shear resistance. The different results will contribute to the development of a recommendation of the Swiss Society of Engineers and Architects (SIA) for the design and the construction of UHPFRC structures [6]. The present experimental campaign was carried out between March and April of 2013. The present article, therefore, shows the first results of this experimental campaign.

The study has highlighted the following points. An important advantage of UHPFRC cellular beams is their optimized use of material in strong-axis bending. Resorting to UHPFRC, a cellular beam reaching a certain web opening can behave just as well as a plain-webbed beam. (PU-1 vs. PU-2). The UHPFRC can replace the shear reinforcement and help to maintain a flexural failure mode even in the presence of openings (PU-1 and PU-2). Higher prestressed forces with large web openings can create higher stiffness and better pre-peak behaviour in UHPFRC beams but, consequently, they can lead to a loss in deflection capacity. Increasing the diameter of the openings affects the stiffness, the deformation capacity, the peak load, and the failure mode of the beams; the first three factors decrease and the failure mode turns from a flexural failure to a brittle shear failure. The decrease on the ultimate load from 587 to 412 kN, between the reference no-openings beam and PU-5 (diameter = 600 mm), leads to the recommendation of limiting the diameter of the circular openings to 50% of the total web height.

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REFERENCES

- [1] Toutlemonde F., Resplendino J. Designing and Building with UHPFRC: State of the Art and Development, Proc. of UHPFRC Symp. in Marseille, Nov. 17-18, 2009, London, 2011, 814 pp.
- [2] Brühwiler E., Moreillon L., Suter R. Bétons fibrés ultra-performants, Proceedings of UHPC symposium in Fribourg (Switzerland), October 26, 2011, Fribourg, 2011, 207 pp.
- [3] Schmidt M. et al. Ultra-High Performance Concrete and Nanotechnology in Construction, Proceedings of Hipermat 2012 symposium in Kassel, March 7-9, 2012, 1058 pp.
- [4] AFGC-SETRA, Interim recommendations, Ultra High Performance Fibre-Reinforced Concretes. Paris, 2002.
- [5] EN 197-1, Cement. Composition, specifications and conformity criteria for common cements, 2011.
- [6] Swiss Society of Engineers and Architects. Recommendation - Ultra-high Performance Fibre Reinforced Concrete (UHPFRC) – Materials, design and construction (in french), Project E-06 April 2013.